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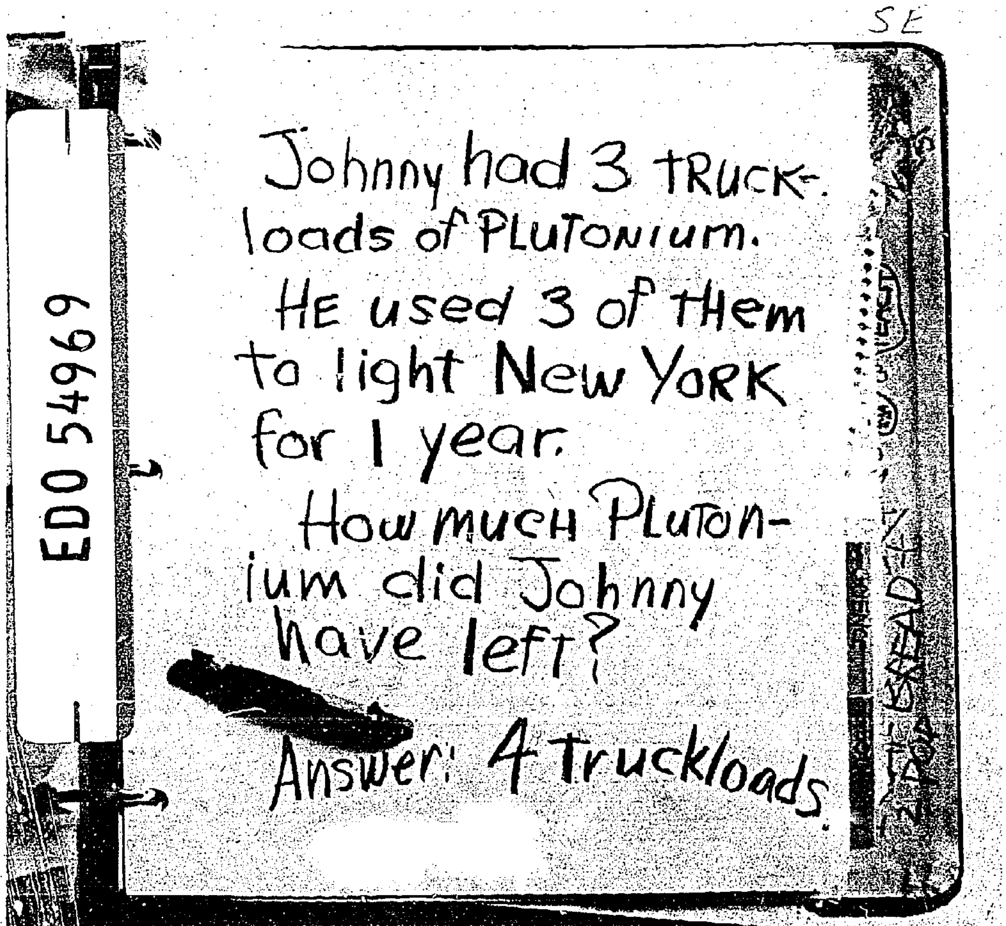
ABSTRACT

The theory of breeder reactors in relationship to a discussion of fission is presented. Different kinds of reactors are characterized by the cooling fluids used, such as liquid metal, gas, and molten salt. The historical development of breeder reactors over the past twenty-five years includes specific examples of reactors. The location and a brief description of various reactors and programs in the United States and foreign countries indicates a large expansion of such facilities in the near future. Lists of relevant reading topics and of motion pictures are included. (TS)



Breeder Reactors

by Walter Mitchell, III and
Stanley E. Turner

Understanding the Atom Series

The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

The Cover

The message in the notebook on the cover sums up the concept of breeder reactors very well. In the future these reactors will produce large amounts of electric energy and still end up with more nuclear fuel than they started with.

Breeder Reactors

by Walter Mitchell, III, and Stanley E. Turner

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United States Atomic Energy Commission
Division of Technical Information

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Foreword

Today our major source of mechanical energy comes from the heat of combustion, the burning of fossil fuels—coal, gas, and oil. We are beginning a shift to nuclear power which, over the coming decades, will make use of the world's vast supply of uranium and thorium and greatly expand our energy potential. The development and use of the breeder reactor will give us an even greater amount of power—perhaps enough for thousands of years—and may radically expand our applications of energy.

When we make full use of energy that breeder reactors will bring us, we may in time be able to use incredibly large amounts of this energy to create new matter, to rebuild, reshape and reuse all matter. This means that our relationship to all our basic needs—food, water, shelter, clothing, a liveable environment—could change drastically.

Eventually we might use matter and energy, time and space, like building blocks. A whole new logic would guide our production and distribution of the necessities of life.

"Waste" would be almost nonexistent. Hence there would be relatively little pollution. Almost everything would be recycled and reused, or returned to nature in a near-natural form and distributed so as to maintain a balanced environment.

Glenn T. Seaborg

Glenn T. Seaborg, Chairman
U.S. Atomic Energy Commission

Breeder Reactors

by Walter Mitchell, III, and Stanley E. Turner

Hopes, Dreams, and Realities

The alchemist's hope of turning base metals into gold—Columbus' search for the new world—the inventor's dream of perpetual motion—the Wright brothers' desire to fly.... For as long as we have any record of [illegible], man has attempted to turn his hopes and dreams into realities. Some efforts failed, while some were successful far beyond their originator's hopes; others, even though they were apparent failures, led to a better understanding of nature's laws.

Nature has yielded some of its secrets to our continuous probing—often with a reluctance that has led to higher levels of scientific inquiry and understanding on our part. Such an area of inquiry is the breeder reactor, which is currently under extensive development throughout much of the world.

Underlying the interest in the breeder reactor is our society's insatiable need for electric power for homes and for the rapidly expanding industry that supports our growing population. **Within the next 10 years, the United States will need new electric power stations with a generating capacity equal to that of all the stations that now exist in this country.** This doubling of power requirements each decade will continue for many years and will be accompanied by an increase in the amount of fuel needed to run the generating plants. Imagine the effect of that enormous demand for fuel on our shrinking supply, and you will see the possible consequences, in only 20 or 30 years, if we do not have the foresight now to prepare for the future.

The demand on our resources of coal, oil, and gas is being relieved by the nuclear power plants we are now using and building.* These plants require their own kind of fuel, however, and its supply is not unlimited. If we continue to build and operate only the types of nuclear power plants that we have today, in just 30 years we will consume the total amount of economically usable nuclear fuel now known to exist. So, while today's nuclear reactors are essential for electric-power generation in the U. S. and other countries, they are not the long-term answer. The answer lies in breeder reactors.

A breeder is a reactor that produces more fuel than it consumes. (In the next chapter we will discuss the materials and processes involved in breeding.) If the breeder can be used in a nuclear power plant, it can provide the heat needed for the generation of electricity and simultaneously produce an excess of fissionable material that can be used to fuel other plants. The answer to this apparent contradiction is that breeder reactors do not give "something for nothing", but produce usable fissionable material from comparatively useless fertile material at a greater rate than the original fuel in the reactor is consumed in the fissioning process.

Fertile materials are abundant and relatively inexpensive, so by converting these materials into fissionable materials the problem of depleting our natural resources is shifted to the distant and very remote future. At the same time, the breeder reactor holds out enticing promises of reducing the cost of electric power generation and reducing its effect on the environment. These promises must be fulfilled before breeder reactors can be built on a large-scale commercial basis, and many people feel that these promises will soon be realized.

In this booklet we will describe breeder reactor research, the different types of breeders, and the future of the program.

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*See the companion booklets in this series, *Nuclear Power Plants* and *Nuclear Reactors*. Also see *Nuclear Reactors Built, Being Built or Planned in the United States*, which is in the reading list on page 44.

The Basic Processes

Breeder reactors are similar in many respects to the nuclear power reactors now in use or being built in many places throughout the world. Breeders, however, are unique in their ability to produce more fissionable material than they consume. To understand how this may be possible—and why other types of nuclear reactors do not "breed"—we must first look at some basic principles.

Fundamental to all nuclear reactors is the fission process. In this process, the impact of a neutron* on the nucleus of an atom of fissionable material can cause the nucleus to break apart, or fission.

Only a few isotopes† available in quantity are capable of sustaining the fission process. These isotopes are uranium-233 (^{233}U), uranium-235 (^{235}U), plutonium-239 (^{239}Pu), and plutonium-241 (^{241}Pu), and the term fissionable material refers to these four isotopes. All four undergo radioactive decay.‡ ^{235}U is the only one that exists in any quantity in nature; the other three, while perhaps present billions of years ago, have essentially decayed completely. Consequently, if we want ^{233}U, ^{239}Pu, or ^{241}Pu now, we must produce it artificially.

In order to create a fissionable material, we use a fertile material, which is a material that will join with or absorb a neutron and result in new fissionable material. The new fissionable material can produce more neutrons by fission, and thus can continue the fissioning process. The fertile materials thorium-232, uranium-238, and plutonium-240 can produce fissionable ^{233}U, ^{239}Pu, and ^{241}Pu, respectively.

*A neutron is a neutral elementary particle, which is found in the nucleus of every atom heavier than hydrogen.

†An isotope is one of two or more atoms with the same atomic number (the same chemical element) but with different atomic weights.

‡Radioactive decay is a spontaneous transformation that results in a decrease, with time, of the number of original radioactive atoms.

Both ^{232}Th and ^{238}U exist in nature, while ^{240}Pu must be created artificially by neutron absorption in ^{239}Pu.

The absorption of a neutron by ^{232}Th or ^{238}U does not result directly in a new fissionable material, but first produces unstable, intermediate products. As indicated in the equations given below, the intermediate products quickly decay to produce the desired fissionable material.

$$(^{232}\mathrm{Th}) + n^* \rightarrow (^{233}\mathrm{Th}) \xrightarrow[\text{decay}]{\text{rapid}} (^{233}\mathrm{Pa}) \xrightarrow[\text{decay}]{\text{rapid}} (^{233}\mathrm{U}) \xrightarrow[\text{decay}]{\text{slow}}$$

$$(^{238}\mathrm{U}) + n \rightarrow (^{239}\mathrm{U}) \xrightarrow[\text{decay}]{\text{rapid}} (^{239}\mathrm{Np}) \xrightarrow[\text{decay}]{\text{rapid}} (^{239}\mathrm{Pu}) \xrightarrow[\text{decay}]{\text{slow}}$$

$$(^{240}\mathrm{Pu}) + n \rightarrow (^{241}\mathrm{Pu}) \xrightarrow[\text{decay}]{\text{slow}}$$

*The letter n represents a neutron. The decay of intermediate products results in each case above in the emission of a beta particle. A rapid decay means that the process will be essentially complete in hours or months, while a slow decay requires hundreds to hundreds of thousands of years.

As the equations show, ^{232}Th is converted to thorium-233, which decays to protactinium-233, which then decays to the desired fissionable material, ^{233}U. When ^{239}Pu is formed from ^{238}U, the intermediate products are uranium-239 and neptunium-239. Plutonium-241 is formed directly from ^{240}Pu.

We have discussed some of the processes involved in producing new fissionable material, and we will now consider another fundamental rule of nature—one concerning the number of neutrons produced in each fission. In Figure 1 a single neutron striking the nucleus of an atom of fissionable material produces fission fragments and the release of free neutrons. The number of neutrons released varies, but is usually more than two. Since only one neutron is needed to continue the fission chain reaction, the other freed neutrons can be used to produce new fissionable material. These excess

neutrons may be (1) absorbed by fertile material to produce new fissionable material, (2) absorbed nonproductively in structural material, fission fragments, control material, fuel, or the reactor coolant, or (3) escape from the reactor and be absorbed in the surrounding shielding material. In developing a breeder it therefore is necessary to design a reactor in which the necessary fissionable, fertile, structural, control, and

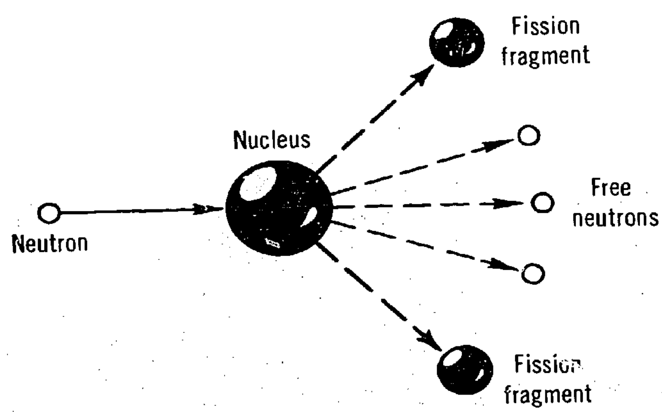

Figure 1 *A fission reaction.*

coolant materials are present and in which as many of the excess neutrons as possible are absorbed in fertile material. There are a number of different ways of doing this.

As stated earlier, the breeder reactor produces more fissionable material than it consumes. This means that for every neutron absorbed by an atom of fissionable material, more than one of the freed neutrons must be absorbed in an atom of fertile material to create more than one new atom of fissionable material. If only one atom of new fissionable material is produced per atom consumed, the amount of fuel (fissionable material) remains constant and breeding does not occur. If less than one new atom is produced, the amount of fuel decreases and the reactor is known as a "converter" or "burner".

Therefore in breeding the average number* of neutrons given off in the fission of a single atom must be greater than two—one to continue the fission process and at least fractionally more than another one to convert fertile material into new fissionable material. This means that breeding may be possible if more than two neutrons are produced, but if two or less are produced, breeding cannot occur regardless of reactor design.

Actually, considerably more than two neutrons per fission are necessary for breeding, because some will be lost through leakage and some lost by nonproductive absorption. The following table gives representative values for the number of neutrons produced per neutron absorbed by the

Average Number of Neutrons Produced* per Neutron Absorbed in Fissionable Material

Type of fissionable material	Thermal neutron absorbed	Fast neutron absorbed
Uranium-233	2.3	2.3
Uranium-235	2.1	2.0
Plutonium-239	1.9	2.4
Plutonium-241	2.1	2.7

*These are approximate values, and the actual value for any given reactor design may differ slightly depending on the details of the design.

different fissionable materials. The numbers indicate that breeding can probably be achieved with the least difficulty and with the greatest efficiency in a fast-neutron† reactor that uses plutonium-239 and plutonium-241 as the fissionable material. The table also indicates that breeding is unlikely, if not impossible, in thermal-neutron† reactors unless they use uranium-233 as the fissionable material.

*In the absorption of a neutron by an atom of fissionable material, various numbers of neutrons are produced; here we are concerned with the number produced on an overall average for each neutron absorbed.

†These terms will be defined later.

At the present time, there are two basic breeder reactor materials "systems":

Fissionable material used	Fertile material used	Fissionable material formed
(1) Plutonium-239	Uranium-238	Plutonium-239
(2) Uranium-233	Thorium-232	Uranium-233

The two breeder materials combinations we will discuss in this booklet are the plutonium–uranium system and the uranium–thorium system, as shown above.

Thermal-neutron or thermal reactors and fast-neutron or fast reactors are important classes of reactors. The neutrons produced in the fission process are generally traveling at very high speeds—about 30 or 40 million miles per hour—and thus are called fast neutrons. If certain materials called "moderators" (water or graphite, for example) are present, the fast neutrons collide with atoms of the moderator and lose speed with each collision.

After bouncing around from atom to atom, the neutrons will reach thermal equilibrium—a term which means that the neutrons have slowed to about the same speed as the moderator atoms. When this slowing down has occurred and thermal equilibrium has been reached, the neutrons are called thermal neutrons and are traveling at an average speed of only about 5000 to 10,000 miles per hour. Thus, the difference between thermal and fast neutrons is mainly a difference in their speed, which is related to the energy of the neutrons.

All reactors contain both thermal and fast neutrons, but the designers can select materials and arrangements that emphasize the thermal or the fast part of the mixture. A thermal reactor is one in which a moderator is present to slow down the neutrons, and the fissions are caused mainly by thermal neutrons. A fast reactor is one in which the amount of moderator material is made as small as possible, so that the fissions are caused principally by fast neutrons. All the very large nuclear power plants in the United States now use thermal reactors, and nearly all these reactors use ordinary water both as the moderator and as the reactor coolant (the fluid that removes the heat generated by the reactor).

The fast reactor is usually regarded as the most promising concept for breeding. In addition to the fact that fission by fast neutrons produces a relatively large number of free neutrons, the fast neutrons are not absorbed as readily as thermal neutrons by the structural material and reactor coolant. Furthermore, the fast neutrons can occasionally cause atoms of fertile material to undergo fission and thus create a few "bonus" neutrons. These bonus neutrons contribute appreciably to the amount of breeding that is possible with fast reactors.

Breeding ratio and **doubling time** are measures of the efficiency of a breeder. The breeding ratio is the number of atoms of fissionable material produced per atom of fissionable material consumed. Doubling time is the time required for a breeder reactor to produce as much fissionable material as the amount usually contained in its core plus the amount tied up in its fuel cycle (fabrication, reprocessing, etc.). Doubling time is a measure of the amount of breeding that is achieved in a given design: The more fissionable material produced during a given period by breeding, the shorter the doubling time. At present, researchers hope to achieve a doubling time of less than 10 years.

The production of excess fissionable material in the reactor is not the whole story, however. Periodically, fuel elements have to be removed from the reactor because (1) the fuel element containers do not last indefinitely and (2) the fuel must be chemically processed. This processing is necessary to recover the fissionable material and to clean the fuel. This cleaning removes the accumulated fission fragments, which increase the unproductive capture of neutrons. Once recovered, the fissionable material can be made into new fuel elements that are loaded back into the reactor (or another one) to continue the power-generating–breeding process. Excess fissionable material produced by breeding can be used in other reactors or stored until a sufficient amount is collected to provide fuel for a new reactor.

We have discussed the processes that may be used to sustain the nuclear chain reaction and, at the same time, result in a net gain of fissionable material. Now let's turn our attention to the ways these processes might be used in practical applications to achieve efficient use of our fuel resources.

Kinds of Breeders

Since one can't tell the players without a program, we will review three types of breeders that show promise. As you will see, there are variations in materials or physical arrangements within some of the "families" of breeders. The categories we will use are fairly standard and are based on the common practice of characterizing the reactor by the kind of cooling fluid it uses.

The reactors we will discuss are the liquid-metal-cooled breeder, the gas-cooled breeder, and the molten-salt breeder. There are other possibilities, and these are mentioned briefly at the end of this chapter.

Liquid Metal

This concept is properly called the liquid-metal, fast-breeder reactor (LMFBR). It is the highest priority civilian nuclear power activity of all the breeder type reactors. Indeed, President Nixon in his Energy Message to the U. S. Congress on June 4, 1971, stated that his program included "a commitment to complete the successful demonstration of the liquid-metal, fast-breeder reactor by 1980".

The basic arrangement of an LMFBR nuclear steam supply is shown in Figure 3. (Each diagram that appears in this section shows steam and water pipes at the right side of the illustration. In a nuclear power plant, these pipes would be connected to the power-generating portion of the plant, which is not shown here.) Since the production of steam is an objective of all the breeders covered in this booklet, we will discuss the overall nuclear steam-supply system rather than just the reactors. The nuclear steam-supply system is the equivalent of the boiler in a fossil-fuel power plant. In all steam power plants, nuclear or fossil, electricity is generated in about the same way. Steam turns a turbine that drives a generator to produce electricity. With its energy almost gone, the steam leaves the turbine and is turned back into water in

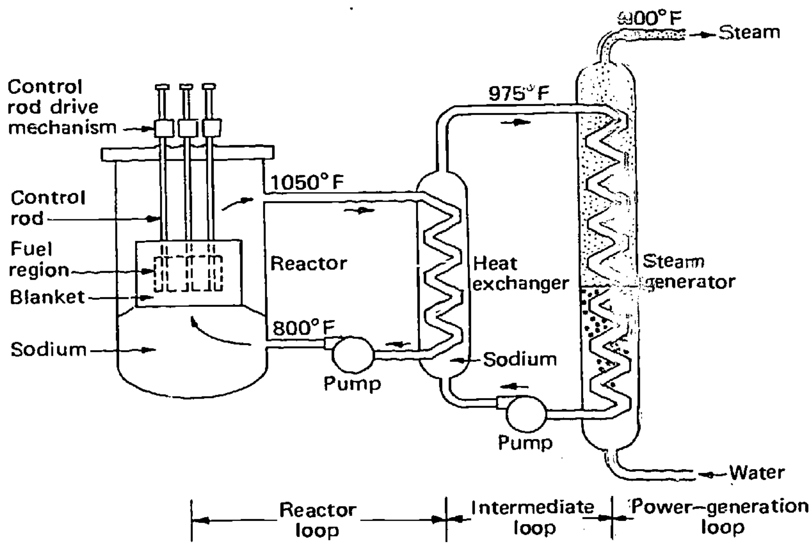

Figure 3 *LMFBR nuclear steam supply.*

a condenser. The water from the condenser goes back to the steam-supply system, where it is formed into steam again. Although it isn't shown, we will call the power-generating portion of the plant the power-generation loop (Figure 3).

As the figure shows, there are three basic loops in a power plant that uses an LMFBR. In addition to the power-generation loop, there are the reactor loop and the intermediate loop. In both the reactor loop and the intermediate loop, the fluid is liquid sodium. The liquid-metal fast breeder operates with fast neutrons. One reason sodium is a good fast-reactor coolant is that it does not moderate, or slow down, neutrons as much as, say, water does. Sodium is also a very good heat-transfer agent and its boiling point is high. Consequently, it can operate at high temperatures without requiring a high pressure to prevent boiling. Now let's return to Figure 3 to see what the temperatures in a typical LMFBR system might be.

In the reactor loop, the sodium is pumped to the reactor vessel at a temperature of about 800°F. In the vessel, the sodium flows through the reactor core, where its temperature is raised to about 1050°F. It leaves the reactor at this temperature and then passes through the heat exchanger, where it heats the sodium in the intermediate loop. This transfer of heat from the reactor loop to the intermediate loop reduces the temperature of the sodium in the reactor loop so that it is ready to be pumped back through the reactor to begin the cycle again and remove more heat.

The sodium in the intermediate loop is heated to about 975°F in the heat exchanger; it then passes through the steam generator and is returned to the heat exchanger. In the steam generator, the intermediate-loop sodium heats the water of the power-generation loop and produces steam at a temperature of 900°F.

The intermediate loop is a safety feature of the LMFBR. The loop separates the radioactive reactor loop from the power-generation loop; this eliminates the possibility of a single leak allowing radioactive material to enter the power-generation loop or resulting in a chemical reaction between the radioactive sodium of the reactor loop and the water or steam of the power-generation loop.

The core of a typical LMFBR consists of a central region of fissionable material (fuel) mixed with fertile material; the central region is surrounded by a blanket of fertile material. The fuel sustains the chain reaction and produces a surplus of neutrons that can be absorbed in the blanket. The absorptions in the blanket convert the fertile material into new fissionable material. The core consists of thousands of small vertical rods arranged so that the sodium coolant can flow along them and remove the heat that they generate. Since the reactor operates at very high temperatures, the rods must be made of special materials.

The fissionable and fertile materials are ceramics, which are able to withstand high temperatures. To protect the ceramics from possible damaging action by the flowing sodium, the fissionable and fertile materials are encased in thin tubes of stainless steel. The ceramic-filled tubes form rods that are about the same diameter as a pencil and are several feet long. Rods such as these are not very rigid, so groups of rods (100 or more) are bundled together, using spacers, and inserted into strong cases to form assemblies.

The assemblies are open at each end, and the spacers hold the individual rods apart so that sodium can flow between them and remove their heat. Many of these assemblies, which are quite strong, are then placed side by side to form the reactor core.

The best-developed forms of the fissionable and fertile materials used in LMFBR's are called oxides, which have been used in other kinds of reactors for years. Carbides and nitrides are also under consideration. The plutonium–uranium system is generally used, and the materials involved are plutonium dioxide (PuO_2) and uranium dioxide (UO_2). When the reactor is ready to start, the fuel portion of the core consists of a mixture of the oxides of ^{239}Pu and ^{238}U, while the blanket contains the oxide form of ^{238}U. A reactor using this combination is said to be fueled with "mixed oxides", which is a reference to the PuO_2-UO_2 portion of the core. The normal initial content of the mixed oxide is about 20% plutonium and 80% uranium-238; as this indicates, a small fraction of plutonium (the basic fissionable material) is sufficient to "drive" the reactor.

Space is provided in the core for another kind of assembly. It is called a control rod, and a number of these regulate the power level of the reactor. The control rods are made of materials that absorb neutrons, and they can be moved vertically in the channels provided for them. By changing the degree of insertion of the control rods in the core, either a smaller or a greater number of neutrons will be available to cause fissions or convert fertile material into fissionable material. Thus, the control rods do precisely what their name implies; they control, or regulate, the reaction rate between the neutrons and core materials.

We have discussed briefly one LMFBR plant, using in our example the materials that are specified most frequently. The physical arrangement we have described uses pipes to connect all major components of the nuclear steam-supply system. As you might have guessed from looking at Figure 3, such a plant uses a loop-type system. Another type of system is called—quite descriptively, but not very elegantly—the pot-type system. This arrangement is illustrated in Figure 4, which shows that the reactor loop is a self-contained unit in a relatively large vessel. There are advantages and disadvantages in both the loop and the pot concepts. For example, the pot-type system is more compact and its core can be cooled more easily if a pump fails, but it may be more difficult to repair.

Gas Cooled

The gas-cooled, fast-breeder reactor (GCFR) has been under study in the United States since the early 1960s and there are several incentives for developing it.

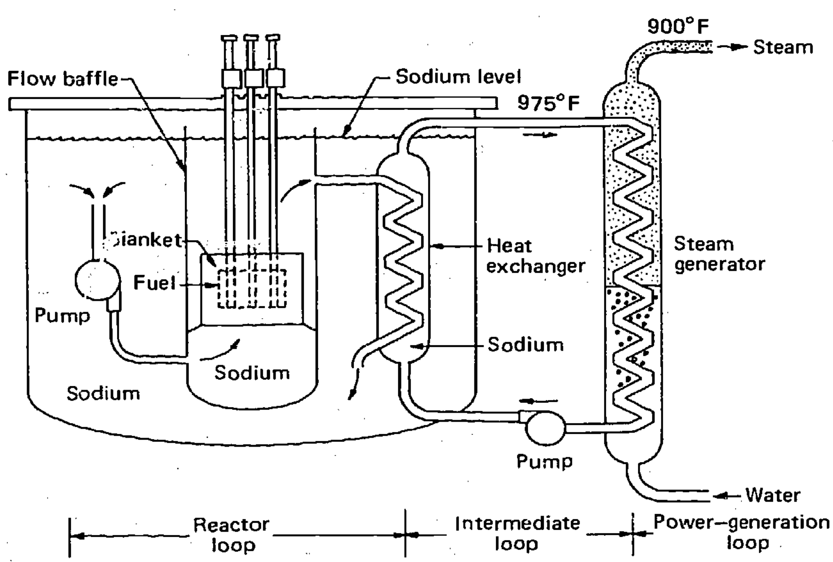

Figure 4 *Pot-type LMFBR nuclear steam supply.*

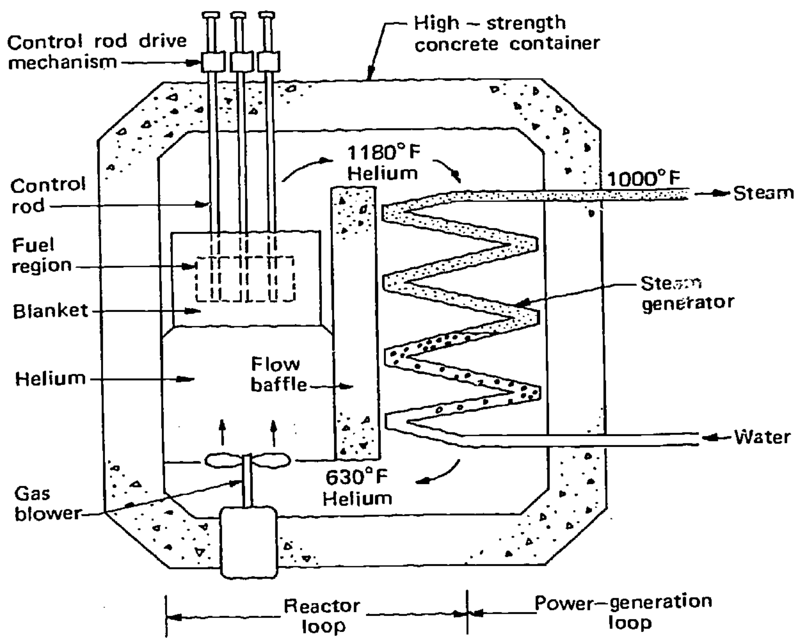

Figure 5 *GCFR nuclear steam supply.*

Figure 5 shows that the GCFR bears some resemblance to the pot-type LMFBR. The system is a closely coupled one in which the reactor cooling fluid is circulated within a single large vessel. Actually, the resemblance between the two kinds of breeders ends about there. The GCFR uses helium as the cooling fluid, although it (or any gas, for that matter) is not as good a heat-transfer agent as liquid sodium.

To qualify as a satisfactory cooling fluid, helium must be used at high pressures and must be passed through the reactor very rapidly. Under these high-pressure and high-velocity conditions the gas is reasonably effective in removing the heat produced by the nuclear processes in the core. The requirements of high coolant pressure and velocity affect adversely the cost of the GCFR because the vessel that contains the reactor must be very strong, and the gas blower must be powerful, but there are some compensating factors.

Since helium does not itself become radioactive or react chemically with water, as does sodium, the intermediate loop between the reactor loop and power-generation loop in the LMFBR is not needed in the GCFR. Thus, the inertness of the helium permits the use of the two-loop arrangement shown in Figure 5. Heat is transferred from the reactor loop directly to the power-generation loop, so there is a reduction in the number of principal components of the plant.

The general arrangement of the core in a gas-cooled, fast-breeder reactor is the same as that in a liquid-metal-cooled breeder. The fuel rods are probably a little larger in diameter for the GCFR, and there are more of them. The fuel materials under consideration are the same as those discussed for the LMFBR (oxides are used now, and carbides and nitrides may be used in the future), but the fraction of PuO_2 in the mixed-oxide fuel is less in the GCFR.

As you can see, there are similarities between the LMFBR and the GCFR. Now for something really different.

Molten Salt

The molten-salt breeder reactor (MSBR) is a concept of American origin and evolution. When the United States started work on a nuclear-powered aircraft in 1947, the molten-salt reactor was among the systems considered for the power plant. Although the aircraft never became a reality, the molten-salt reactor did. The successful operation of an experimental molten-salt reactor, coupled with major advances in development that make possible a simpler plant, has led to the consideration of the MSBR, which is shown in Figure 6.

The schematic drawing for the MSBR looks a lot like the one for the loop-type LMFBR; each shows a reactor loop, an intermediate loop, and, of course, a power-generation loop.

Salts are the key to the MSBR. Many salts are chemical compounds composed of a metal and an element such as chlorine, fluorine, or bromine. The best example of a salt is

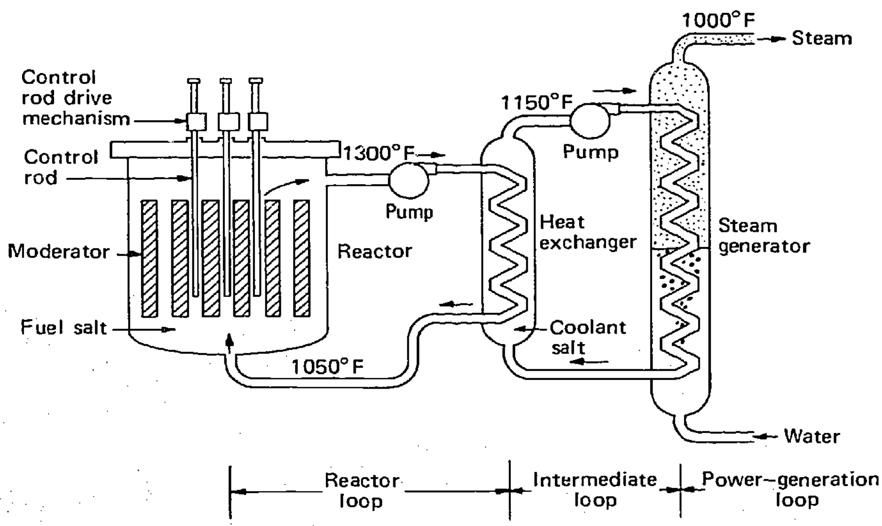

Figure 6 *MSBR nuclear steam supply.*

common table salt, NaCl, in which sodium (Na) is the metal and chlorine (Cl) is the other element. Most people don't think of salts in the molten form, but the designers of the molten-salt reactor did and they developed an interesting plant.

The basic concept of the molten-salt breeder is one in which the fissionable material and the fertile material are circulated as a liquid through a region in which the fission process can occur. The fuel is a liquid called the fuel salt and consists of a combination of four fluorine-salt compounds. The metals used with fluorine to form the salts are uranium, thorium, lithium, and beryllium. The uranium and thorium are the fissionable and fertile materials used in the breeding process.* Since the uranium–thorium system operates on thermal neutrons, the MSBR is called a thermal breeder. Lithium and beryllium, which constitute most of the fuel salt, are used to dilute the fissionable and fertile materials to the proper concentrations.

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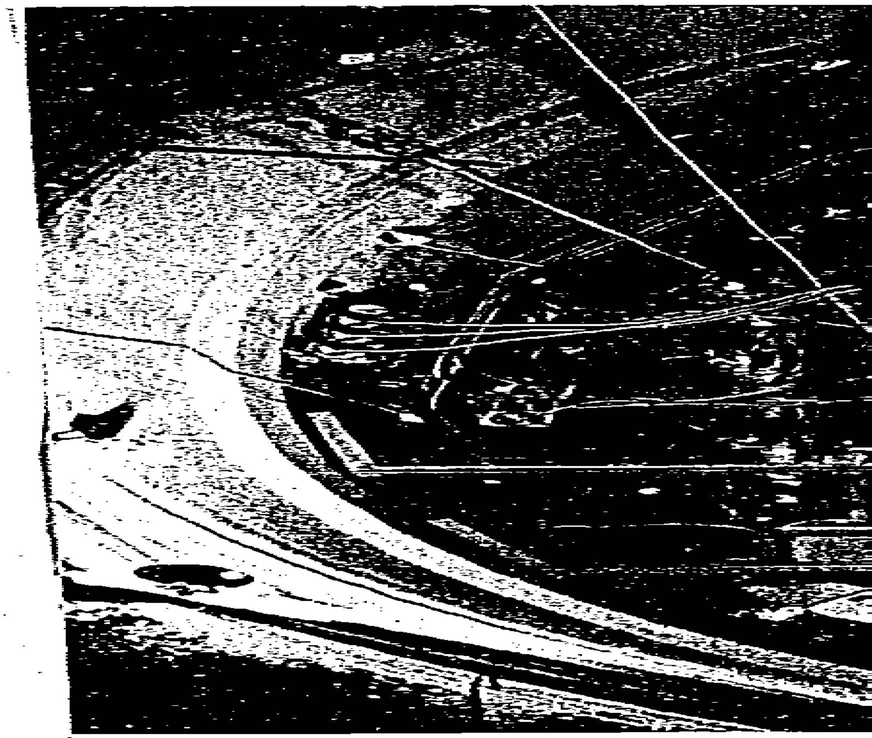
*See *Thorium and the Third Fuel*, a companion booklet in this series.



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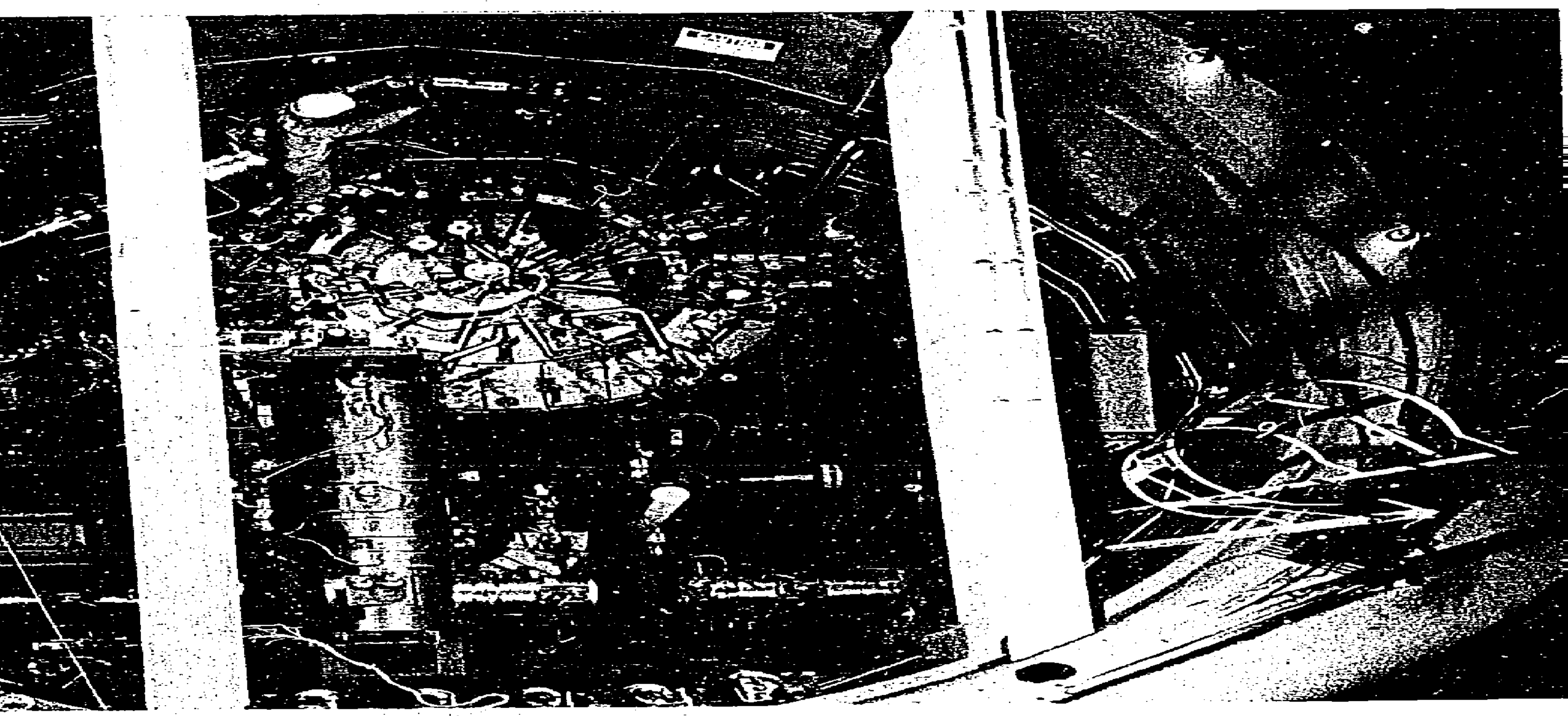


1 *technician stands atop the thermal shield of the Molten*
r during the reactor's installation.

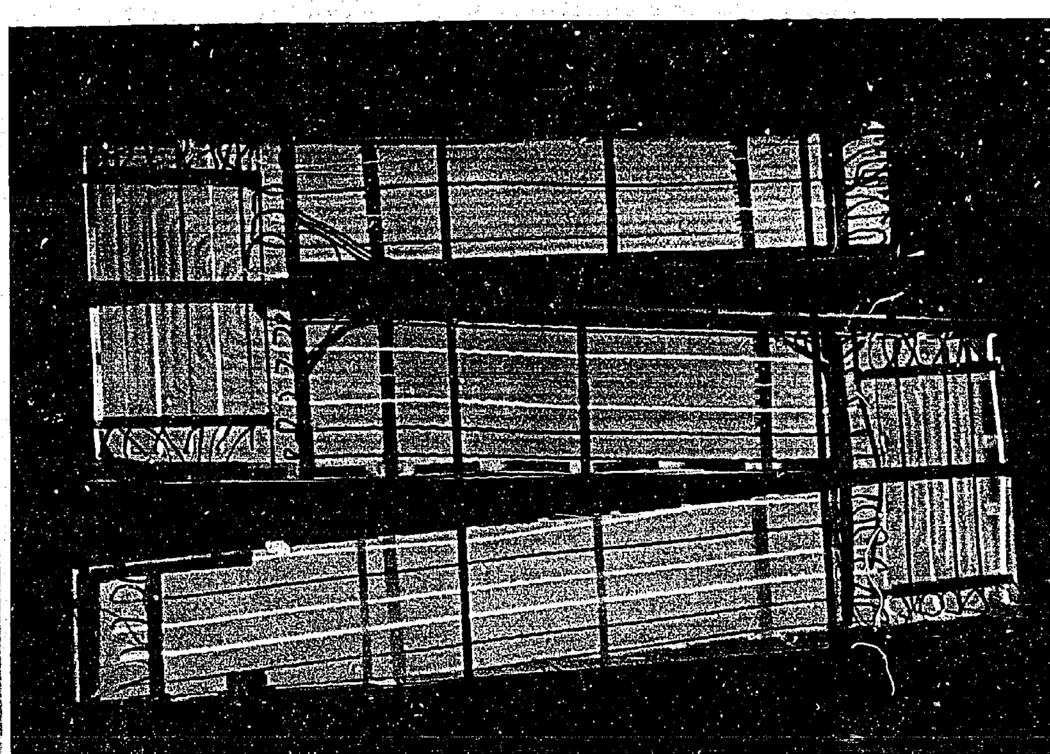
:ore region of the reactor has fixed, vertical "logs" noderator material to slow down the neutrons. The lerator logs, which are graphite, are spaced apart so fuel salt can flow between them. When the fuel salt core, the combined moderating effect of the salt the graphite is such that the reactor can sustain the action. There is no possibility of a chain reaction he core (in the loop piping, for example), because ion requires a complex geometrical arrangement of

fuel salt circulates in the reactor loop during 1. As the salt flows through the core region, it arily becomes a part of the core and generates heat the fission process that occurs in some of its ents. When a particular volume of salt leaves the core

region, the reaction in that volume stops; the salt then becomes the circulating fluid that transports the heat from the reactor to the heat exchanger.

In the heat exchanger, the energy (heat) produced in the reactor is transferred to the coolant salt of the intermediate loop for subsequent transfer to the water of the power-generation loop. The fluid in the intermediate loop is called the coolant salt because it, too, is a molten salt and because it removes heat from the fuel salt of the reactor loop. The mixture contains no fissionable or fertile materials, since there is no requirement for them in the intermediate loop.

Figure 8 *Primary heat exchanger of the Molten Salt Reactor has a heat-transfer area of nearly 259 square feet. Heat is removed from the coolant-salt mixture in the air-blast radiator and is dissipated through a metal stack to the atmosphere. The coolant flows through tubes ¾ inch in diameter and 30 feet long. The tubes are arranged in 10 banks with 12 tubes in each bank. The photograph was taken with the light emitted from the molten salt mixture.*



The coolant salt is a mixture of two salts that possess suitable qualities for the service intended and are relatively inexpensive.

The molten-salt breeder reactor holds promise as a system capable of producing low-cost power and, at the same time, using the abundant resources available for the uranium–thorium fuel cycle. Much development work is necessary, but, if the molten-salt concept proves commercially feasible, the United States will have developed a system that can play an important role in meeting future requirements for electric power.

Other Possibilities

Two other reactor concepts are being considered as possible breeders. The first of these is the light-water breeder, which has been under study in the U. S. for a number of years. The other is the steam-cooled breeder, which has been the subject of work in the U. S. and in other countries.

The light-water breeder is based in large part on the well-developed technology of commercial nuclear power plants that use pressurized-water reactors. The specification of the core for a light-water breeder (a thermal breeder, operating on the uranium–thorium cycle) represents a principal challenge to the reactor designers because the system must operate at highest neutron efficiency to breed. If the physics performance of the core can be shown to be satisfactory (from the breeding and economic points of view), most of the rest of the plant design can be based on an established foundation of experience.

Several groups in the United States have studied the steam-cooled breeder concept, but it appears that the most thorough investigation has been carried out by the West Germans. The studies indicate that the steam-cooled breeder is faced with a dilemma: At high steam pressures, the cost of the electric power produced is acceptably low but the reactor barely breeds; if the steam pressure is lowered, the breeding performance of the reactor improves but the cost of the electric power it produces increases. Research on the steam-cooled breeder has all but stopped.

In the next chapter we will review some of the events and accomplishments that have brought the breeder reactor to its present state of development.

Early Achievements and Milestones

In November 1946—only 4 years after the world's first reactor operated in Chicago*—the first fast-neutron reactor began operation at the Los Alamos Scientific Laboratory in New Mexico. The code name for plutonium (Forty-nine) and the location of the reactor (in a canyon) reminded the researchers of the lyrics of a song, and so they named the reactor "Clementine" after that song. She was a small experimental reactor, fueled with plutonium and cooled by liquid metal (mercury), whose core could produce up to 25 kilowatts of heat. This first fast reactor was operated until 1953 and contributed much to our store of fundamental scientific knowledge.

Several experimental fast-critical assemblies have been built in this country. Two of the better known are the "Lady Godiva" and "Jezebel" test assemblies at the Los Alamos Scientific Laboratory. These names were used because the reactors were bare, fully-exposed assemblies, as illustrated in the photo of Jezebel (Figure 9). These assemblies helped prepare the way for later breeder reactor development.

Probably the most significant milestone in the history of the breeder was the construction and operation of the Experimental Breeder Reactor No. 1 near Arco, Idaho. This reactor, usually referred to as EBR-I, began operation in 1951 and soon thereafter accomplished the first of two major feats for which it is justly famous. On December 20, 1951, four 200-watt light bulbs blazed into brilliance, powered by energy derived from fission in the fast-reactor core of EBR-I. These four glowing light bulbs symbolized the beginning of the nuclear power industry and marked the world's first electric power generation by a nuclear reactor plant. The next day, December 21, 1951, all the electricity for the EBR-I building was supplied by the reactor and its associated

*See *The First Reactor*, another booklet in this series.

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fact, a real physical phenomenon. In July 1953 it was announced that measurements had confirmed that EBR-I had proven the basic principle of breeding. Although years of hard work and further research lay ahead in applying the breeding principle to larger reactors, the EBR-I demonstration gave a tremendous psychological boost to the scientists and engineers working toward breeder reactors and moved the breeder concept from the realm of hope to an area of more solid scientific foundation.

During its dozen years of operation, EBR-I was a rich source of information on fast-breeder reactors. The significance of its role was publicly acknowledged in 1966, when the EBR-I site was designated a Registered National Historic Landmark by the U. S. Department of the Interior. The inscription on the plaque honoring the reactor reads, in part, "... this site possesses exceptional value in commemorating or illustrating the history of the United States."

Reactors in the United States

A number of reactors have been built in the United States for the purpose of demonstrating or developing the breeder concept. As described in the preceding section of this booklet, the world's first real breeder reactor was EBR-I, which had a core heat power rating of 1400 kilowatts and produced around 200 kw of electric power.* The fuel portion of the reactor core was quite small, and this is a characteristic of liquid-metal, fast-breeder reactors (LMFBR's). In EBR-I the fuel was in the usual form of small rods, and these rods occupied a space about the size of a regulation football.

The information and encouragement that scientists, engineers, and planners received from the success of EBR-I led to the design and construction of two larger fast-breeder reactors, the Experimental Breeder Reactor No. 2 (EBR-II) in Idaho and the Enrico Fermi Atomic Power Plant on the shore of Lake Erie in Michigan. Both these reactors are essentially pilot-plant LMFBR's, which were originally designed to demonstrate electric-power production with fast-reactor cores and to extend the store of knowledge that will ultimately make possible the construction of commercial nuclear power plants using breeder reactors.

EBR-II is designed to produce 62,500 kilowatts of heat. Its use has been oriented to irradiation testing of fuels and other materials for the fast breeder. A view of the EBR-II complex is shown in Figure 11. The plant has operated satisfactorily for a number of years. Operations started in the late fall of 1961, and EBR-II began producing electric power in August 1964. Fuels and materials tests began in April 1965.

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*In liquid-metal-breeder reactor plants designed to produce electricity, the anticipated electric power rating is about 35 to 40% of the core heat power rating.

The Enrico Fermi Atomic Power Plant No. 1, named in honor of the famous nuclear scientist,* is shown in Figure 12. This plant is licensed to operate at a core heat rating of 200,000 kw. Although a series of operating problems delayed sustained power-demonstration runs, the Fermi plant has provided valuable insight into some of the problems that may face large, commercial breeder plants.

In the picturesque hills of Arkansas, a small fast reactor known as the Southwest Experimental Fast Oxide Reactor (SEFOR) is now operating. The specific purpose of this reactor is to provide more information regarding the dynamic performance of reactor cores that use the mixed plutonium–uranium oxide fuel referred to earlier in the chapter "Kinds of Breeders". SEFOR is a sodium-cooled reactor whose core is designed to produce 20,000 kw of heat, with provisions for possible future modifications to increase this to 50,000 kilowatts. The plant does not generate electricity. Truly a cooperative project, SEFOR is sponsored by American industry, the USAEC, West Germany, and an organization called Euratom.†

The U. S. Atomic Energy Commission has embarked on a comprehensive program aimed at developing the technology needed for the design, construction, and operation of fast-breeder, nuclear power plants. One of the most important items in this program is a large test reactor known as the Fast Flux Test Facility (FFTF). It is located near Hanford, Washington, and is scheduled for initial operation in the mid-1970s. A powerful facility from which meaningful test data can be obtained in a short time, the FFTF will have a core heat rating of 400,000 kw. The reactor is cooled by liquid sodium, and nine special areas are provided in the core

*Enrico Fermi was the leader of the team of scientists that built the first nuclear reactor. See *The First Reactor*, another booklet in this series.

†Euratom is the European Atomic Energy Community. This organization promotes nuclear growth in Europe. Its members are Belgium, France, Federal Republic of Germany, Italy, Luxembourg, and The Netherlands.

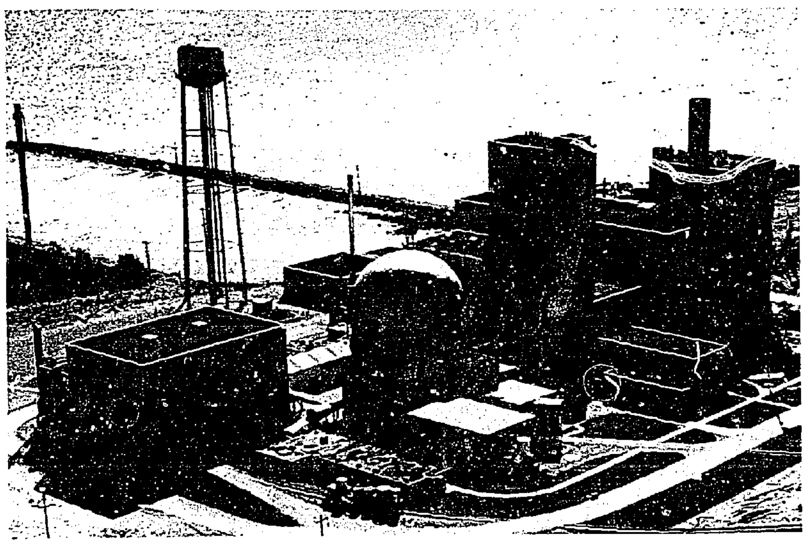

Figure 12 *An aerial view of the Enrico Fermi Atomic Power Plant.*

for experiments. Although the FFTF reactor will be a fast-neutron reactor, it will not be a breeder. It will be used primarily to test fuels and other materials for future fast-breeder reactors. (See Figure 2 on page 12.)

Earlier in this booklet, we discussed the molten-salt breeder reactor and the light-water breeder. Although there are no actual plants that use these reactors at present, there are two developments worth mentioning.

The molten-salt reactor experiment at Oak Ridge National Laboratory in Tennessee began operation in 1965 and has furnished important data on the materials and systems required for a possible MSBR. Second, the design of a light-water breeder core is progressing, and such a core may be installed in an already existing nuclear power plant around the middle of the decade. It is appropriate that the plant selected for the breeder core is the Shippingport Atomic Power Station, which started operation in Pennsylvania in 1957 and was the first nuclear power plant to be operated commercially by an electric utility in the U. S.

Programs in the United States

In 1945 Enrico Fermi said, "The country which first develops a breeder reactor will have a great competitive advantage in atomic energy." During the quarter century since Fermi's statement, there have been significant developments in the technology of breeder reactors. The United States has now reached the point at which a systematic, carefully organized, and coordinated effort for future breeder development is necessary. A major part of this effort has been defined and will be carried out under the direction of the Atomic Energy Commission through its Liquid Metal Fast Breeder Reactor Program. Although there are several independent projects in the United States, sponsored generally by reactor manufacturers and electric power companies, the AEC's LMFBR Program is being aided in its implementation by the nuclear industry and the National Laboratories.*

The LMFBR Program Plan, published by the Atomic Energy Commission, covers a period of about 20 years and culminates in the 1980s with the introduction of commercial nuclear power plants using fast-breeder reactors. The stated objective of the plan is "... to achieve, through research and development, the technology necessary to design, construct, and safely, reliably, and economically operate a fast-breeder power plant in the utility environment; and to assure maximum development and use of a competitive, self-sustaining industrial capability in the program."

The LMFBR Program Plan divides the required development work into nine technical areas: (1) plant design, (2) components, (3) instrumentation and control, (4) sodium technology, (5) core design, (6) fuels and materials, (7) fuel recycle, (8) physics, and (9) safety. Implementation of the plan calls for the construction of a variety of test facilities as well as the use of facilities already in existence.

*The National Laboratories are contractor-operated installations that perform research and development for the AEC.

Foreign Developments

Many foreign countries have breeder-reactor programs. The programs vary widely in size, ranging from small, laboratory-type experiments of a specific nature to the construction of complete power plants. On the basis of their past experience and present activities, the United Kingdom, France, West Germany, and the USSR are considered the leading nations outside the United States in breeder-reactor development.

One of the similarities in the foreign programs is their strong emphasis on the design and construction of prototype power plants. The foreign programs will rely on the experience obtained with the medium-size prototype plants to provide the design bases for large commercial units. All the prototype plants are based on liquid-metal, fast-breeder reactors.

United Kingdom

As a part of their large nuclear-power program, the British have been engaged in the study and development of fast-breeder reactors since 1951. In Britain, as well as the other countries we will discuss in this chapter, principal interest lies in the sodium-cooled breeder concept.

In 1954 two experimental zero-power reactors were placed in operation at the Atomic Energy Research Establishment at Harwell. Their purpose was to provide basic physics information on fast-reactor cores and to verify that breeding could be a practical process.

On the basis of the information gained through analytical and experimental work, the United Kingdom Atomic Energy Authority (UKAEA) in 1955 began construction of a 60,000-kilowatt (heat) experimental power plant at Dounreay on the coast of Scotland. The Dounreay Fast Reactor (DFR), which is shown in Figure 13, first operated in late 1959 and, after a long shakedown period, reached its design power in 1963.

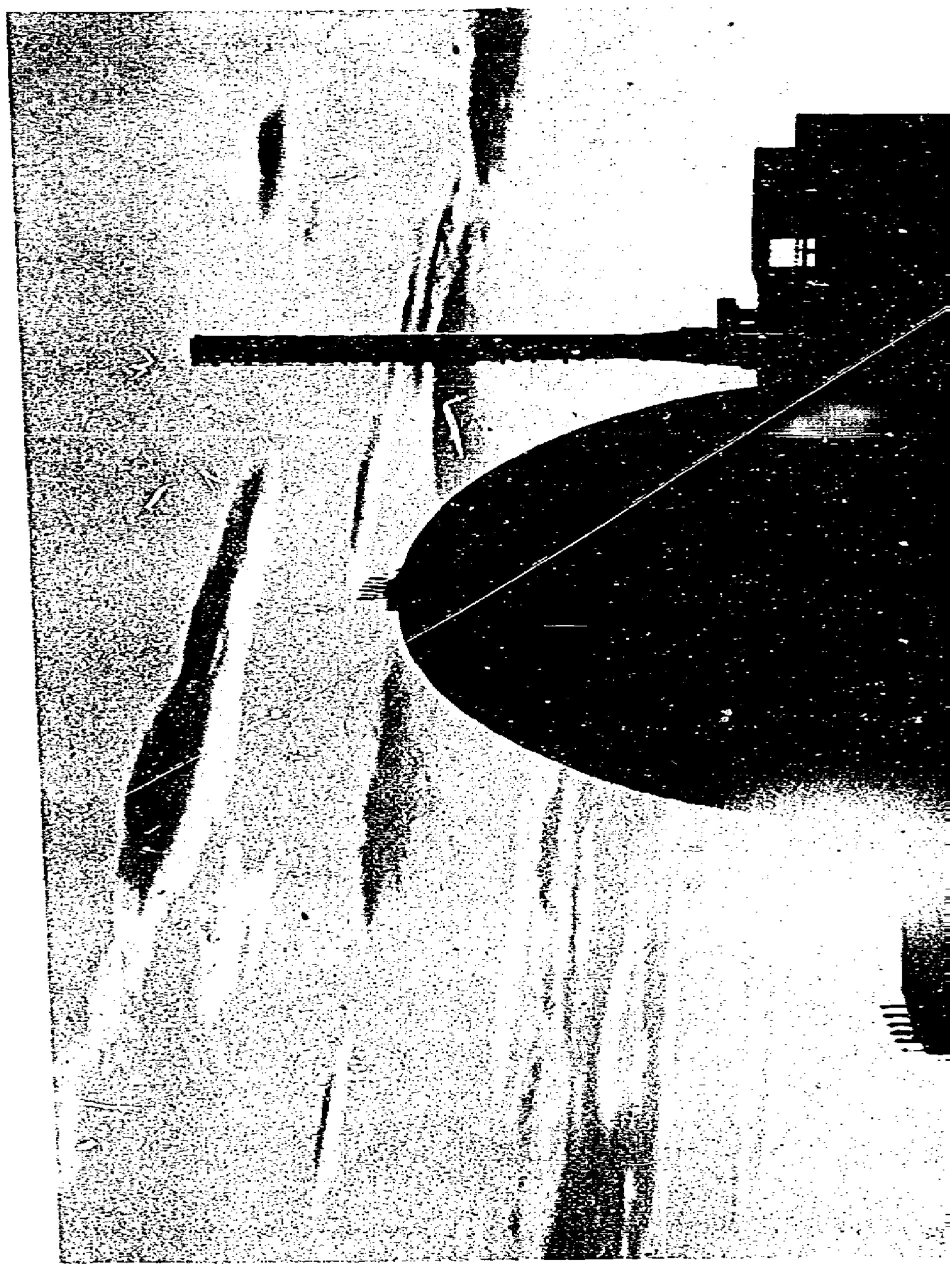

Figure 13 The Dounreay Fast Reactor in Scotland.

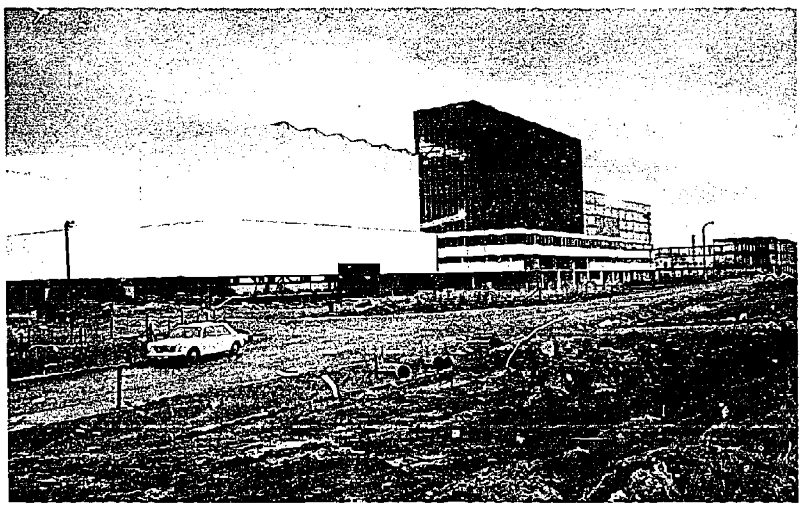

Figure 14 *Great Britain's Prototype Fast Reactor.*

The British decided fairly early to build an intermediate-size, prototype breeder reactor—that is, one considerably larger than the DFR, but not as large as commercial stations will be. In 1966 work began on the construction of the 250,000-kw (electric power) Prototype Fast Reactor (PFR), also at Dounreay. A view of the PFR, which will generate electricity for the North of Scotland Hydro Electric Board beginning in the early 1970s, is shown in Figure 14.

France

In France, nuclear research is carried out largely by the Commissariat a l'Energie Atomique (C.E.A.), which corresponds to the U. S. Atomic Energy Commission. The C.E.A., which was created in 1945, has developed many nuclear reactors for research, production of materials for nuclear weapons, submarine propulsion, and electric-power generation. The nuclear power plants in France have generally been designed by the C.E.A., but they are operated by a nationalized electrical-power organization.

The C.E.A. began fundamental research on liquid metals for nuclear power plant applications in 1953 at its Fontenay-aux-Roses Research Center. French work on fast breeders has continued and was given a substantial boost in 1962, when a contract was signed between the C.E.A. and Euratom for the design, construction, and operation of a fast reactor and associated facilities.

The focus of the C.E.A.–Euratom program is the sodium-cooled Rapsodie reactor (Figures 15 and 16). Rapsodie does not generate electric power, but its core was designed to produce 20,000 kilowatts of heat that is dissipated to the atmosphere through heat exchangers that operate on the same principle as automobile radiators.

Construction of Rapsodie began in 1962, and the reactor began operation in 1967. It has performed well and has given the French confidence in their capability to proceed with the next major step in a national breeder program: The construction of a 250,000-kilowatt (electric) prototype power plant. The plant is called Phenix and is scheduled to begin power operation in 1973 at Marcoule in southern France.

West Germany

The development of nuclear power plants in the Federal Republic of Germany got off to a late start. Following World War II, essentially no work was carried out in the nuclear field until 1955. Germany is unlike many countries in that it has no large national agency comparable to the U. S. Atomic Energy Commission. The Federal Government does give financial assistance to the individual German States for nuclear programs, but the States have considerable independence under the German system of government.

The Germans are making up for their late start in nuclear energy by establishing research centers, using their outstanding industrial capability, constructing many reactors, and undertaking joint programs with other countries and

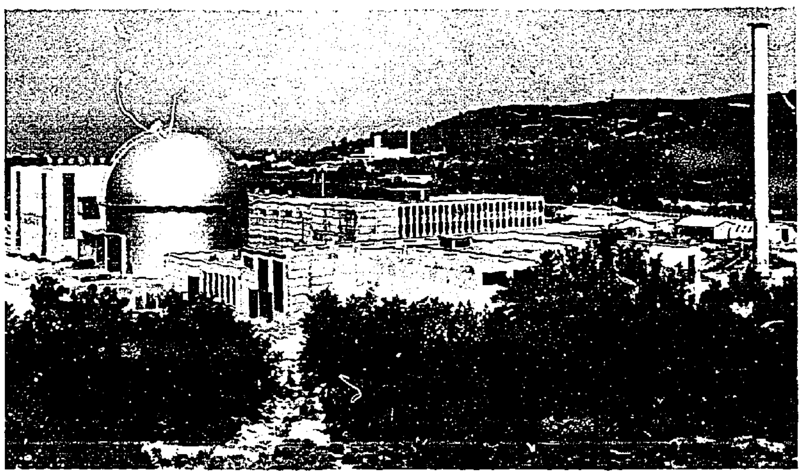

Figure 15 *The French reactor Rapsodie.*

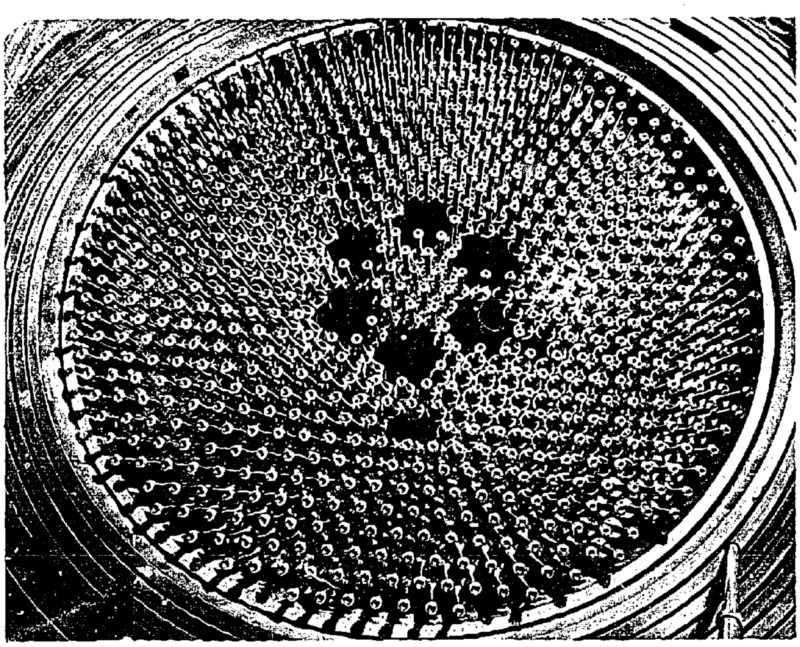

Figure 16 *The core of Rapsodie reveals the numerous core assemblies of this small reactor.*

with Euratom. The Karlsruhe Nuclear Research Center (Figure 17) is the most important applied research installation engaged in German breeder-reactor activities.

Work on fast breeders has been carried out at Karlsruhe since 1960, with Euratom support of the breeder work starting in 1963. Several reactors are located at the Center, and among those having a direct bearing on the German

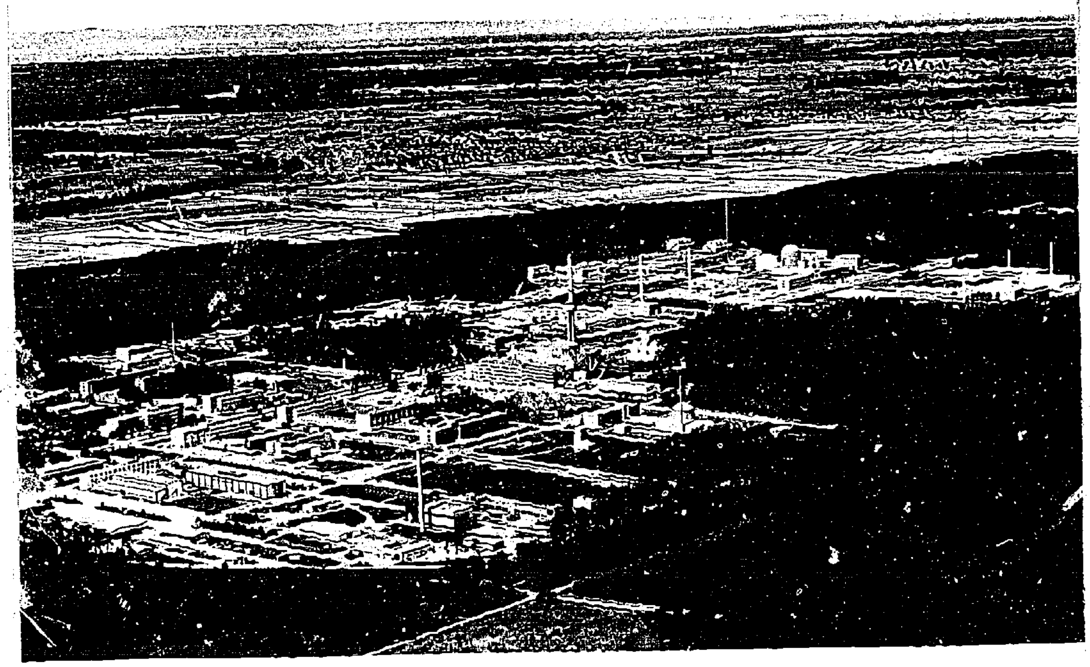

Figure 17 *The Karlsruhe Nuclear Research Center in West Germany.*

fast-breeder program are SNEAK (Figure 18) and KNK (Figure 19). SNEAK is a zero-power facility that is used for physics research, while KNK is a power-producing nuclear plant. Although the sodium-cooled KNK is designed to operate initially as a thermal-neutron reactor, it will be converted to a fast reactor in the early 1970s. The Germans will continue to gain information and experience through participation in the SEFOR project in the United States.

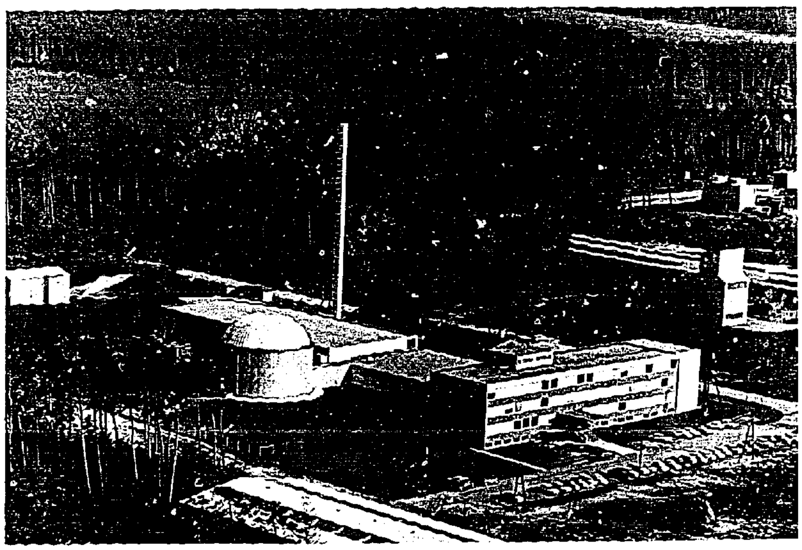

Figure 18 *The zero-power reactor SNEAK.*

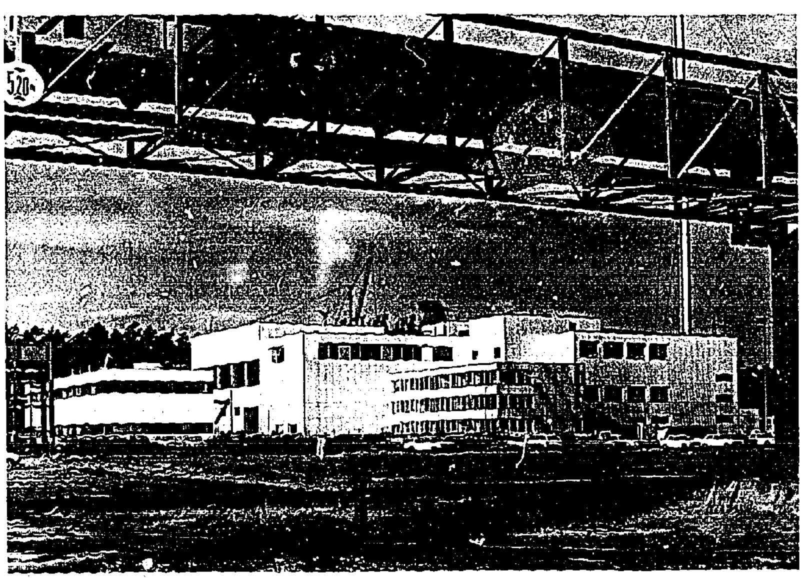

Figure 19 *West Germany's KNK experimental nuclear power plant.*

Figure 20 *Russian model of a very large breeder reactor.*

A prototype sodium-cooled breeder, designated SNR, is scheduled to start power operation in the mid-1970s. SNR will have a power output of 300,000 kw (electric) and is a cooperative project between industry and government in Germany, Belgium, The Netherlands, and Luxembourg. The German role in the SNR project is the dominant one, but the Belgian and Dutch contributions are substantial.

USSR

The USSR has the most ambitious breeder-reactor construction program in the world. The size of the plants under construction (the largest has an electric power output of 600,000 kw) is impressive, but there have been significant delays in the schedules of some of the plants.

A low-power, experimental, fast-reactor core began operation at Obninsk, near Moscow, in 1955. This facility and others led the way for the construction of the BR-5 reactor, which began operation in 1959. The BR-5 core is rated at 5000 kw (heat), and this energy is dissipated to the atmosphere through heat exchangers.

On the basis of the experience gained from the BR-5, the Russians took a giant step and announced in 1964 that they would build a breeder plant for power production and water desalination near the shore of the Caspian Sea. The BN-350, as the plant is called, will produce 150,000 kw of electric power and enough process steam to desalt about 30,000,000 gallons of water per day. If the plant were used solely to produce electric power, it would have an output of 350,000 kw. The BN-350 was originally scheduled to begin operation in the late 1960s, but it is estimated now that the plant will start up in the early 1970s.

The USSR is also constructing an advanced breeder, the BN-600, a 600,000-kw (electric) breeder power plant that is due to be completed in the mid-1970s. The Russian breeders of the future will probably be based on information obtained from the BN-600 and from a test reactor called the BOR-60. A model of a possible future Russian breeder reactor (Figure 20) shows the fuel and blanket portions of the core and the reactor vessel.

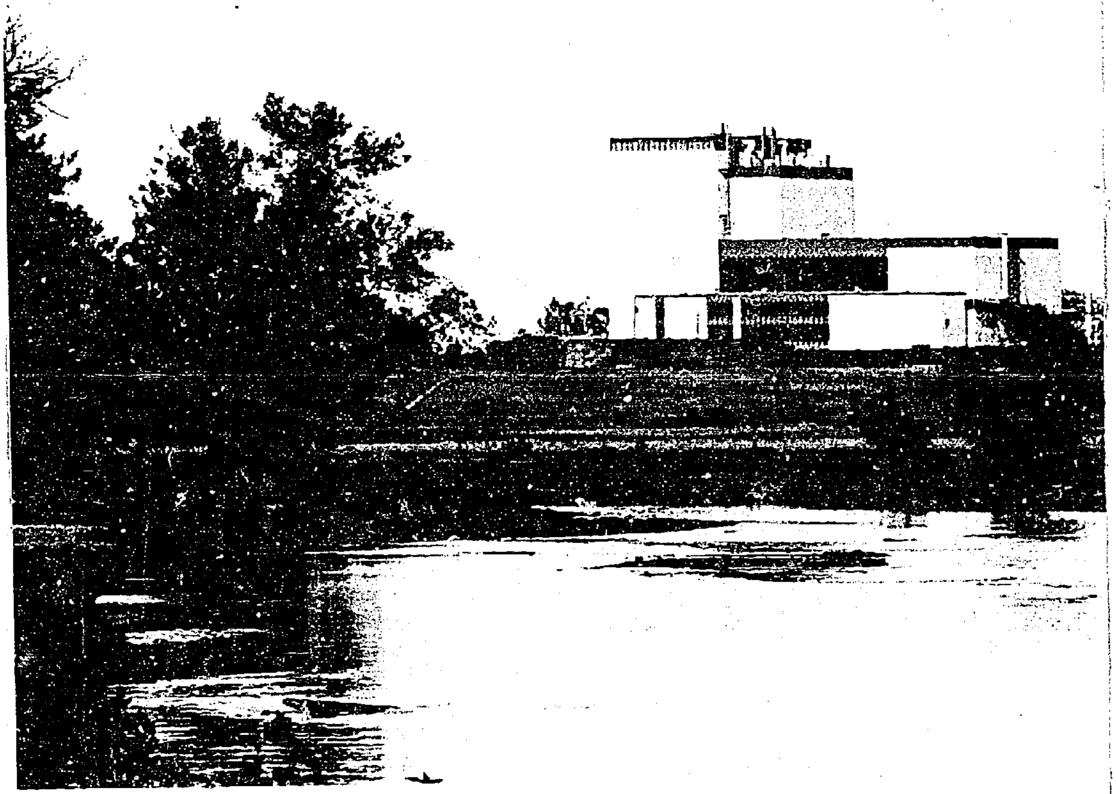

Figure 21 *The Fort St. Vrain Nuclear Generating Station under construction at Platteville, Colorado, will be a high-temperature, gas-cooled thermal reactor (HTGR). It operates on a thorium-uranium fuel cycle and uses helium as a coolant. Experience with this reactor will contribute a great deal to breeder reactor development because helium has special advantages as a coolant for fast breeder reactors.*

A Look to the Future

What does the future hold for the breeder reactor? What will its impact be on our society? The answers to these questions can only be based on speculation, but an objective appraisal of power requirements, fuel resources, and nuclear reactor development reveals that the future is indeed bright for the breeder. Let's look at the present and then 30 years in the future—a span roughly equal to the period from a human's birth to the time he has matured, married, and established a family.

At present, essentially none of the electric power that we use is supplied by breeder-reactor plants. However, 30 years from now about one American out of three, on the average, will probably have his electric power requirement met by a generating plant using a breeder reactor. Remember that there will be many more Americans then than there are now, and that the per capita use of electric power will be much higher. With this in mind, we'll close by saying that, 30 years from now, U. S. breeder-reactor plants will probably have a capacity greater than the combined capacity of all the power-producing plants of all types in our country today.

Reading List

Articles

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The following reports are available from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402:

Major Activities in the Atomic Energy Programs, January–December, issued annually, U. S. Atomic Energy Commission, about 400 pp., $1.75.

The Nuclear Industry, revised annually, Division of Industrial Participation, U. S. Atomic Energy Commission, price varies with each issue.

Forecast of Growth of Nuclear Power (WASH-1139), Division of Operations Analysis and Forecasting, U. S. Atomic Energy Commission, January 1971, 187 pp., $1.50.

Civilian Nuclear Power—The 1967 Supplement to the 1962 Report to the President (TID-23729), U. S. Atomic Energy Commission, February 1967, 56 pp., $0.40.

Motion Pictures

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C. 20545 and from other AEC film libraries.

In Search of a Critical Moment, 28 minutes, color, 1970. Produced by AEC's Argonne National Laboratory. This film tells the story of the Zero Power Plutonium Reactor, which is a special test reactor designed to supply information essential to the development of economic fast-breeder, central-station, nuclear-power plants. The film shows the construction of the ZPPR by the Argonne National Laboratory, its many safety features, plutonium handling and storage, the computer that analyzes the data obtained by the reactor, and the fuel loading and attainment of reactor criticality.

Principles of Thermal, Fast and Breeder Reactors, 9 minutes, color, 1963. Produced by AEC's Argonne National Laboratory. This animated film explains nuclear fission, the chain reaction, and the control of this reaction in three basic types of reactors. It describes the principles of fast and thermal reactors and introduces the concepts of the moderator and reflector. The breeder principle is described, and plutonium and thorium cycles are presented.

A Breeder in the Desert, 29 minutes, black and white, 1965. Produced by AEC's Argonne National Laboratory. Argonne's Experimental Breeder Reactor No. 2 at the National Reactor Testing Station in Idaho is shown in detail, and many of the features and operating characteristics of a large-scale fast-breeder reactor are described. The EBR-II Fuel Cycle Facility, first nuclear fuel reprocessing plant completely integrated with a reactor, is shown in operation.

PHOTO CREDITS

Cover courtesy North American Rockwell.

Page facing page 1	Lick Observatory
Figure 2	Battelle-Northwest
Figures 7 & 8	Oak Ridge National Laboratory
Figure 9	Los Alamos Scientific Laboratory
Figures 10 & 11	Argonne National Laboratory
Figure 12	Power Reactor Development Company
Figures 13 & 14	United Kingdom Atomic Energy Authority
Figures 15 & 16	Commissariat a l'Energie Atomique (C.E.A.), Saclay. Photography by La Photothèque
Figures 17, 18, & 19	Kernforschungszentrum Karlsruhe

Walter **Mitchell, III,** is a Vice President in the consulting firm Southern Nuclear Engineering, Inc. He is a graduate of the Georgia Institute of Technology, and his career in the nuclear industry began with design work on prototype ship-propulsion reactors. During the period since that early work, Mr. Mitchell has been active in the design, analysis, and evaluation of essentially all types of nuclear plants. He is the author of numerous technical reports and articles, many of which have appeared in the AEC publication *Reactor and Fuel-Processing Technology* and its predecessor, *Power Reactor Technology*. Mr. Mitchell is coauthor of another booklet in this series, *Nuclear Power Plants*.

Stanley E. Turner, a reactor physicist, has been engaged in reactor design and analysis, development of analytical techniques and computer programs, and fuel-management studies since 1957. He has gained broad experience in calculating the neutron-physics behavior of complex reactor systems, as well as in general reactor plant design and analysis. Until 1957, he was engaged in fundamental physics research with accelerators and in laboratory and field investigations of radiological characteristics of fallout products of atomic bomb detonations. Dr. Turner has B.S. and Ph. D. degrees from the Universities of South Carolina and Texas, respectively. Currently, he is Vice-President, Physics, of Southern Nuclear Engineering, Inc.

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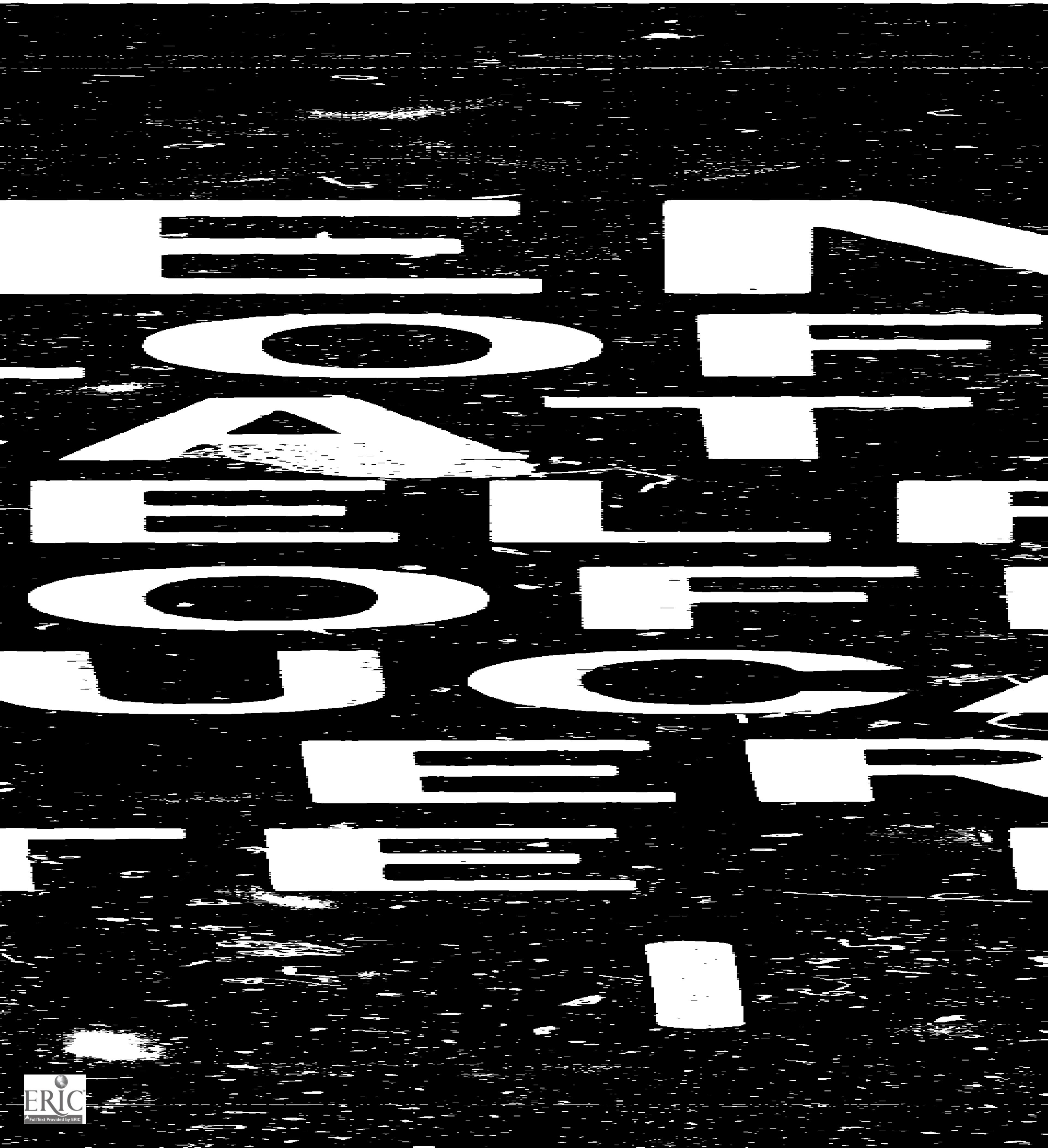

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